Solidification Microstructure of Rheocast Hyper-Eutectic Al–18Si Alloy

Mohamed Ramadan*[1,2], Naglaa Fathy [3]

[1]Central Metallurgical R& D Institute, P.O. Box 87 Helwan, Egypt

[2]College of Engineering, University of Hail, P.O. Box 2440 Hail, Saudi Arabia

[3]Physics Department, College of Science, University of Hail, P.O. Box 2440, Hail, Saudi Arabia

*[1,2]mrnais3@yahoo.com; [3] naglaaf2002@yahoo.com

Abstract

The effect of semi-solid processing using a cooling plate on the morphology of primary Si particles for hyper-eutectic aluminum–silicon alloy was investigated. Semi-solid slurry was prepared using the cooling plate technique and was cast in sand molding strips with constant width of 25mm and length of 150 mm with the thicknesses of 6 and 25 mm. The optimum conditions to obtain optimum primary Si particle globularity and distribution for present hyper-eutectic Al-Si alloy were found at low fraction of solid ranges (f_s =0.01 to f_s=0.05) using cooling plate technique. Increasing the fraction of solid in the slurry increases the chance of abnormal large primary Si particles, especially, for fraction of solid above 0.05. The presence of abnormal large Si particles is the result of the primary Si agglomeration and coalescence which appears by increasing fraction of solid above 0.05. The hardness value depends on the morphology of distributed primary Si.

Keywords

Semi-solid Processing; Hyper-Eutectic; Cooling Plate; Microstructure; Al-Si

Introduction

Al alloys are group of casting materials that are, in tonnage terms, the second most popular after ferrous castings. The Al alloys have been divided into several systems identified based on their alloying elements by the American Aluminum Association (AAA). Aluminum-Silicon (Al–Si) alloys are the most abundant among cast alloys and have wide-spread applications, especially in the aerospace and automotive industries [Robles Hern´andez and Sokolowski, 2006]. The presence of coarse primary Si particles (PSPs) in the microstructure of the Al–Si hypereutectic alloys has been identified as the main limitation for their industrial use. Even with the use of silicon modifiers and high cooling rates, the primary Si particles can only be reduced in size. Although the primary Si particles are very hard and certainly increase locally the wear resistance of the alloy, they are brittle and easy to crack exposing the soft Al matrix to extreme wear resulting in catastrophic failure of automotive or aerospace components [Sokolowski and Mazurek, 1987; Lasa and Rodriguez-Ibabe, 2003]. The common microstructure of hypereutectic Al–Si alloys is composed of primary silicon particles (PSPs) and eutectic structure of α-Al and Si. The high strength and wear resistance of these alloys are attributed to the presence of hard silicon particles (both primary Si and eutectic Si) [Baiqing et al., 2003; Kim et al., 2001]. However, due to the formation of faceted and blocky primary Si during conventional processing, this group of alloys experiences low ductility and poor machining properties, which greatly restricts their application in potential fields.Refinement of primary silicon particles is an effective way to overcome these disadvantages [Lu et al.,2007]. Since the discovery of the unique rheological behavior of nondendritic semi-solid slurries in the early 1970s [Spencer et al.,1972 and Kirkwood,1994], several new semi-solid metal-forming (SSMF) processes based on nondendritic semi-solid slurries have been developed.

Recently, some experiments [Lu et al,2007; Chen et al.,2004; Kapranos et al., 2003; Lee et al., 1995] only focus on the effect of semi-solid processing using thixoforming or thixocasting on the size of PSPs, and little work has been made on the effect of rheocasting using cooling plate on size and globularity of PSPs for fabrication of net-shape castings. The most commonly used shaping routes for Al-foundry alloys are sand and permanent mold casting. The low production cost of such manufacturing routes involves certain drawbacks, including the formation of porosity, hot tears, and segregation which may act as potential crack initiators during service operation. Therefore, there have been considerable efforts to minimize these problems which have resulted in introducing more advanced casting routes such as squeeze casting or rheocasting. In this context, rheocasting has become to

play an increasing importance as an alternative technique to minimize the shortcomings of the as-cast products in comparison to other conventional casting routes [Lashkari, et al., 2006].

In this study, the optimization and the effect of semi-solid processing using cooling plate on refinement of the PSPs for hypereutectic Al–Si alloys in sand molds (as a final net-shape products) was investigated. Much attention was paid to the relation between fraction of solid value and size and globularity of the PSPs.

Experimental

Melting and Casting

The alloy was melted in 30 kg batches medium frequency induction furnace. The chemical composition of alloy samples is shown in Table 1.

TABLE 1 CHEMICAL COMPOSITION (IN WT. %) OF AL-SI HYPEREUTECTIC ALLOY

Si	Fe	Cu	Mn	Mg	Zn	Ti	V	Al	T_L(Liquids)	Ts(Solidus)
18.70	0.63	4.76	0.01	0.67	0.03	0.04	0.01	rest	688 ^{0}C	563 ^{0}C

The melt charge of approximately 5 kg was removed from the furnace to the pouring system, at the desired temperature; and the melt charge is poured over a cooling plate inclined at the known angle (*see* Fig. 1) to the horizontal (10°) and to flow into the sand(6% sodium silicate) mold cavity.

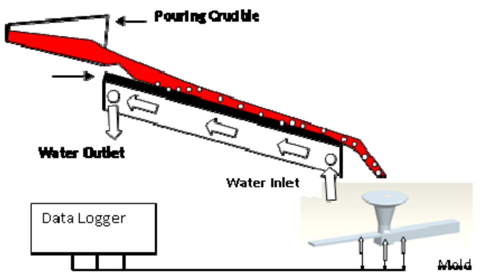

FIG. 1 POURING SYSTEM WITH COOLING PLATE.

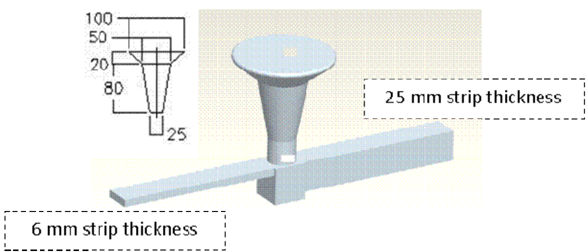

FIG. 2 DESIGN USED FOR CASTING SPECIMENS (UNIT IN mm)

Strips with constant width 25mm and length 150 mm, thicknesses of 6 and 25 mm as shown in Fig. 2 were investigated in this study. Pouring (before cooling plate) was carried out at a range of temperatures between 690 and 740°C to assess the effect of primary Si fraction solid. The cooling slope of 550mm length, 150mm width and 10mm thickness was made from gray cast iron coated with boron nitride and cooled with circulating water. The temperature of liquid metal (before cooling plate) and slurry (after cooling plate) was measured by a K- type thermocouples inserted in the crucible and the mold.

The cooling curve of hyper-eutectic Al-Si alloy during solidification from the liquid state is shown in Fig. 3 without using the cooling plate using thermocouple inserted in the bottom of pouring cup. The pouring temperature of 740 ^{0}C was used for measuring the cooling curve. It is clear that the alloy under investigation has a wide solidification range (125 ^{0}C) suitable for semi-solid processing.

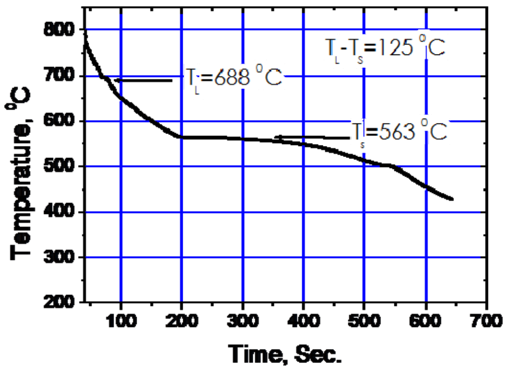

FIG. 3 COOLING CURVE OF HYPER-EUTECTIC Al-Si ALLOY.

Fraction of Solid

Fraction of solid was predicted using image analysis after quenching samples of 10x10x10 mm cut from the ordinary cast (without cooling plate) and heated with the rate of 100 ^{0}C/min and soaked at different temperatures for 5 min before water quenching. Microstructure examination for primary Si particles was performed for large area of sample to obtain representative and reproducible results. Typically, many areas from the same sample were measured. Previous studies [Robles Hernandez and Sokolowski, et al., 2006] showed that the solidification of the Al enriched regions promotes a rapid increase in solid fraction from α-Al halo until the Al-Si eutectic. The temperature did not rise until sufficient thermal energy was provided to melt the eutectic. A rapid temperature rise was noted when the melting of the eutectic was over. Therefore, in present study, the small range of fraction of solid has been selected to study the effect of semi-solid processing using cooling plate on refinement of the PSPs for hypereutectic Al–Si alloys. Increased interest in semisolid metal processing

during the recent years has created the need for the accurate evaluation of the volume fraction of solid in semisolid alloys as a function of temperature, since this parameter controls to a large extent the rheological behavior [Flemings,1991; Joly, Mehrabian, 1976; Chen and Tsao, 1997] and the evolution of microstructure [Hardy and Voorhees, 1988; Loue and Suery,1995; Tzimas, and Zavaliangos, 2000] in the semisolid state. Thus, this parameter is of critical importance, for both fundamental work and the control of the process. The quenching experiments do, however, reveal the presence of liquid at medium and low volume contents of solid. The temperatures measured at the end of the cooling plate using thermocouples inserted in the bottom of pouring cup are used for prediction of primary fraction of solid using the data from quenching samples. In this study, the decreasing pouring temperature increases the fraction of solid. Fraction of solid predicted using image analysis after quenching samples and calculated by Scheil model showing is close to each other that may explained generally,by the low fraction of primary Si used for this study.

Microstructure Observation and Hardness Test

Rectangular samples were cut from the strip casting. Microstructure and hardness measurement for cross section surface at 20 mm distance from pouring base were studied. Metallographic specimens were all cut from the same position of the casting samples, then mechanically ground and polished through standard routines (polished using range of 200 to 800 grinding paper, then polished with 6 micron diamond paste and etched with a 0.5% HF solution) before they were examined with Zeiss light optical microscope fitted with Hitachi digital camera. The primary silicon particle size, primary silicon particle sphericity ($S=4\pi$(area of the grain/grain circumference^2)), were measured and analyzed with IMAGE C analysis software(with errors 6%). Brinell hardness tests were also performed using 2.5 mm diameter ball and 62.5 kg load (with errors 4%).

Results and Discussion

Microstructure

Solidification of hypereutectic Al-Si begins with the precipitation of primary silicon from the melt as temperature falls under the liquidus. Figs. 4 and 5 show the effect of semi-solid processing using cooling plate on the structure of the semi solid processed hypereutectic Al-Si alloy hypereutectic for 25 mm and 6 mm strip thicknesses respectively. Present and previous studies [Wang , et al., 2004] have indicated that cooling rate (strips wall thickness) has less effect on both primary silicon and primary aluminium co-existed for aluminium phosphide free refining alloys.

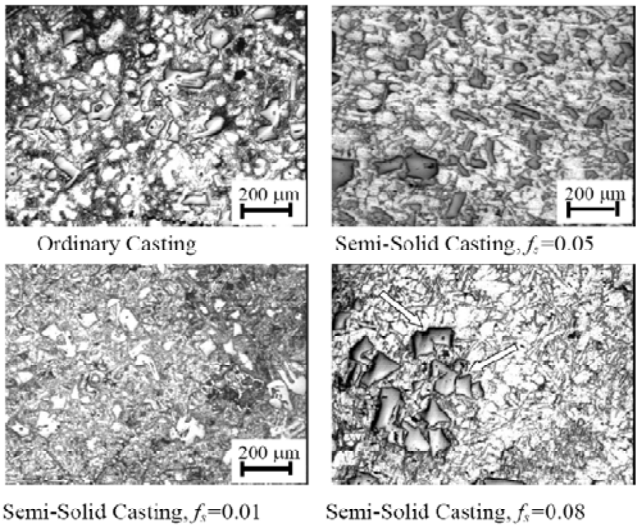

FIG. 4 EFFECT OF SEMI-SOLID PROCESSING ON THE STRUCTURE OF HYPER-EUTECTIC AL-SI ALLOY FOR 25 MM STRIP THICKNESS, THE ARROWS INDICATE FOR COALESCENCE.

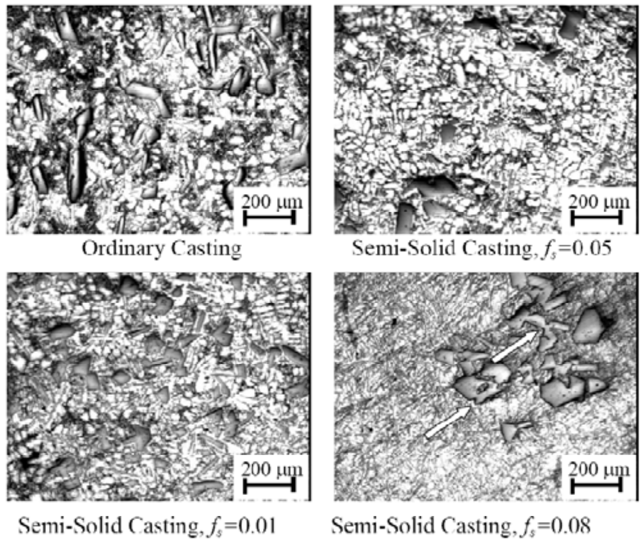

FIG. 5 EFFECT OF SEMI-SOLID PROCESSING ON THE STRUCTURE OF HYPER-EUTECTIC AL-SI ALLOY FOR 6MM STRIP THICKNESS, THE ARROWS INDICATE FOR COALESCENCE.

Generally, this study shows that the ordinary casting has a large faceted primary Si; on the other hand primary Si in semi solid casting becomes relatively finer and more globular compared with ordinary one for fraction of solid lower than 0.05. At a fraction of solid above 0.05 huge silicon block agglomerates start to appear.

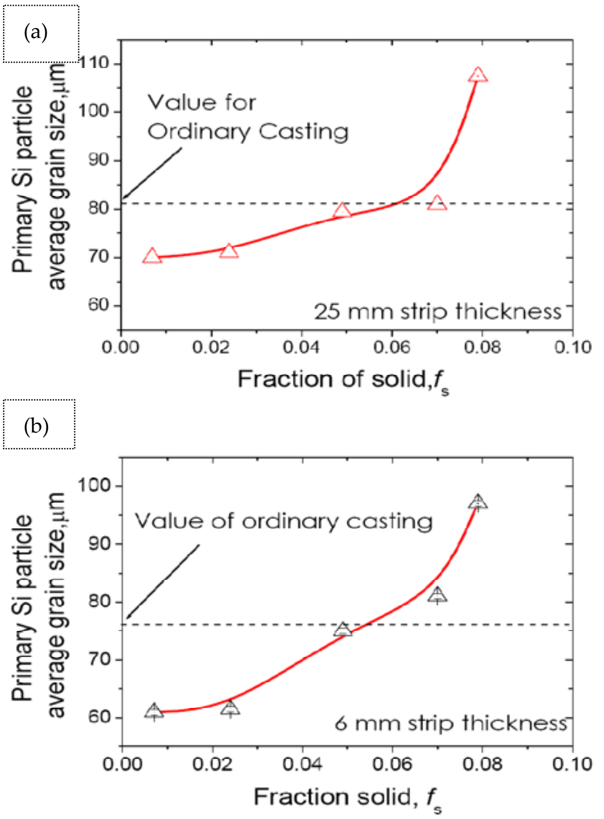

FIG. 6 EFFECT OF SEMI-SOLID PROCESSING ON (A AND B) PRIMARY SI PARTICLE GRAIN SIZE FOR 25 MM AND 6 MM STRIP THICKNESSES.

Figs. 6 and 7 show the effect of fraction of solid on the average Si particle size and Si particle sphericity. It is clear that semi-solid processing affects the primary Si size and changes its distribution. For low fraction of solid (f_s ≤0.024), fine globular primary Si was obtained, and further increasing fraction of solid results in coarse grain Si of primary Si. Our present study and previous[Ramadan, et al., 2006; Muumbo, , et al., 2004] studies are in good agreement of the point that the shape and size of the primary particle phases are affected with the use of cooling plate due to the resultant high cooling rate of melt . High cooling rate of the melt increases the number of the effective nucleus decreasing the average primary silicon particle size especially for low fraction of solid [Bower and Flemings, 1967; Motegi , et al.,2002; Cardoso Legoretta, et al., 2007]. The fluid flow down the slope provides shear to the initial dendrites to aid the dendrite breakup, transfer the newly formed grains throughout the melt and homogenize the temperature of the melt. Homogenization of the concentration gradients will tend to lead to suppression of dendrite formation and hence spheroid formation.

By increasing fraction of solid, the formation and evolution of rheocast microstructure is frequently associated with the breakup of faceted silicon particles to small pieces followed by agglomeration and sintering of these pieces to form some large clusters. However a study conducted by one of the authors on the evolution of the rheocast microstructures in Al–Cu alloys indicated that seemingly large clusters of smaller particles were in fact single entities (deformed and ripened dendrites) with very complicated shapes. For this reason the terms ''pseudo-cluster'' and ''pseudo-particle'',were used in the previous publications to characterize the rheocast microstructures [Spencer and Mehrabian, Flemings, 1972; Falak and Niroumand, 2005; Doherty, et al., 1984].

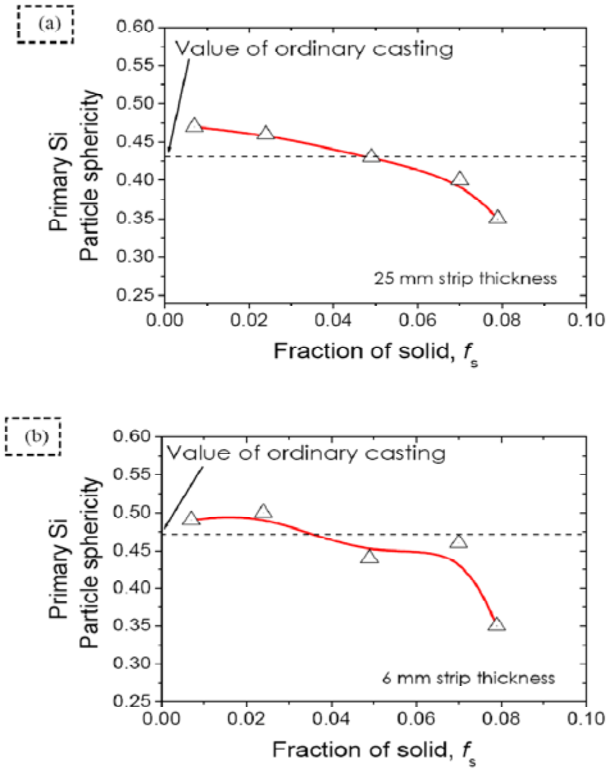

FIG. 7 EFFECT OF SEMI-SOLID PROCESSING ON (A AND B) PRIMARY SI PARTICLE SPHERICITY FOR 25 MM AND 6 MM STRIP THICKNESSES.

In case of mechanical stirring rheo-casting, a new mechanism was therefore proposed for the evolution of rheocast microstructures [Niroumand and Xia, 1998]. This mechanism considers that growth of the primary features is most affected by the fluid flow if their nucleation events have taken place on the crucible walls. The features which nucleate in the bulk of the melt or are washed away from the crucible walls into the bulk of the melt will have very small velocity relative to the flow. These features will be only carried along with the melt and will not be affected significantly by the applied shear rate. On the other hand, the proposed mechanism discussed that the primary features which nucleate on the crucible walls undergo a period of accelerated coarsening followed

by deformation and compaction under the turbulent flow while attached to the crucible walls. After this period, penetration of the high velocity flow between the arms of the primary features becomes difficult and the entrapped liquid between the arms becomes more or less quiescent. From this time on, the high velocity flow will mainly affect the outer parts of the features which are in direct contact with the melt. Depending on the processing conditions, the features will grow until they reach a critical size after which they will be separated from the walls by the stirring action of the melt. The effects of flow will be even more diminished after separation of the primary features as pointed out before and the growth will proceed in a more normal fashion in the bulk of the melt. Agglomeration, according to this mechanism, can take place between the pseudo-clusters rather than the so-called primary particles.

In the present study the cooling plate is used for production of the semi-solid slurry. while, the rheocast microstructures are the result of a combination between the rapid solidification and the flow-related fragmentation of the dendrites in semi-solid state. At low fraction of solid, the cooling rate due to cooling plate and velocity of slurry flow of solid have a considerable effect on PSP producing PSP with a size of about 70 μm and 60 μm for 25 mm and 6 mm strip thicknesses respectively. At high fraction of solid, the amount of solid (PSP) in the slurry increases, which nucleate in the cooling plate wall washed away from the wall into the slurry, and will have very small velocity relative to the flow of slurry. This result together with the convection effect may lead to the presence of abnormal large Si particles in the semisolid state, as shown in Figs. 4 and 5, which was the result of the agglomeration and coalescence of the Si particles.

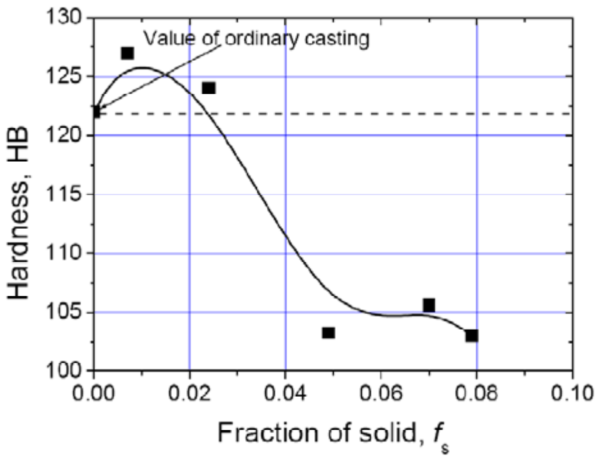

FIG. 8 HARDNESS AS A FUNCTION OF FRACTION OF SOLID FOR 25 MM STRIP THICKNESS.

Hardness

Fig. 8 shows the effect of fraction of solid on hardness. It is clear that the hardness increases firstly by increasing fraction of solid due to fine and good distributed primary Si and after that further increament in fraction of solid(f_s >0.024) leads to the hardness decreasing due to the primary Si particles agglomerationsTop = Bottom =25mm =0.98"

Conclusions

The effect of the semi-solid processing on the solidification microstructure and hardness of hyper-eutectic Al-Si alloy was investigated, which led to the following conclusions:

1. Structure improvement for the rheocast hyper-eutectic Al-Si alloy for fraction of solid less than 0.05. The optimum conditions to obtain optimum primary Si particles globularity and distribution for present hyper-eutectic Al-Si alloy were found at low fraction of solid ranges (f_s =0.01 to f_s=0.05) using cooling plate technique.

2. Rheo-casting of hyper-eutectic Al-Si alloy using cooling plate at fraction of solid less than 0.024 produce PSP with a size of about 70 μm and 60 μm for 25mm and 6mm strips wall thicknesses consequently.

3. Increasing fraction of solid in slurry increases the chance of abnormal large primary Si particles formation, especially, for fraction of solid above 0.05 due to agglomeration and coalescence of the primary Si

4. The hardness increases firstly by increasing fraction of solid due to fine and good distributed primary Si and after that farther increasing fraction of solid above 0.05 leads to the decreasing hardness due to the primary Si particles agglomerations.

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